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METHOD FOR REDUCING BIAS ERROR IN A VIBRATING STRUCTURE
GYROSCOPE

This invention relates to a method for reducing bias error in a Vibrating Structure Gyroscope which is particularly, but not exclusively, suitable for use 5 with such gyroscopes made from silicon.

Micro-machined Vibrating Structure Gyroscopes (VSG) are widely available at low cost. Such gyroscopes have been fabricated using a wide range of vibrating structures which include tuning forks, planar rings, beams and oscillating disk structures. The basic operating principles of all these 10 gyroscopes are essentially the same in that the vibrating structure is driven into resonance to provide a carrier mode motion. When the structure is rotated around an axis orthogonal to the linear motion provided by the carrier mode motion, Coriolis forces are developed. These forces are directed along the remaining orthogonal axis and cause the vibrating structure to vibrate in a 15 second mode of oscillation called the response mode. The motion of this response mode is in phase with the carrier mode motion with the amplitude being directly proportional to the applied rotation rate.

Such Vibrating Structure Gyroscopes are suitable for use in a wide range of high volume applications such as in the automotive field for automatic braking 20 systems, roll over prevention and car navigation. The low cost and small size of these Vibrating Structure Gyroscopes makes them attractive for other uses such as inertial navigation and platform stabilisation. However their use in the latter applications has been limited by the restricted performance that can be achieved, particularly in terms of bias stability (output in the absence of an 25 applied rate). It is necessary to achieve improved performance from these Vibrating Structure Gyroscopes to make them suitable for applications requiring greater accuracy.

A major limitation which restricts the performance of vibrating structure Coriolis gyroscopes is quadrature bias error. Quadrature bias errors arise due 30 to the imperfections in the geometry of the vibrating structure. These imperfections cause oscillation of the response mode which is in phase

quadrature (i.e. has a 90° phase relationship) to the motion induced by applied rotation rates, and may be present even when the gyroscope is not rotating. The magnitude of these signals may also be large in comparison to the required in-phase signal which provides the rotation rate information. Recovering the 5 required rotation induced signal in the presence of a large quadrature signal places stringent requirements on the phase accuracy of the detection system. Accurately phased electronics enable the quadrature signal to be substantially rejected. However practical limitations on the accuracy with which this phasing can be set mean that some of this signal will typically remain to contaminate the 10 true rotation induced in-phase signal. This limitation is a major source of error for this type of Vibrating Structure Gyroscope.

There is therefore a need for a method for further minimising the impact of quadrature error on vibrating structure Coriolis gyroscope performance.

According to one aspect of the present invention there is provided a 15 method for reducing bias error in a Vibrating Structure Gyroscope having a vibrating structure, primary drive means for putting the vibrating structure into carrier mode resonance, primary pick-off means for sensing carrier mode motion, secondary pick-off means for sensing response mode vibration of the vibrating structure in response to applied rotation rate, secondary drive means 20 for applying a force to control the response mode motion, closed loop primary control loops for maintaining a fixed amplitude of motion at the primary pick-off means and for maintaining the drive frequency at the resonance maximum, and secondary control loops for maintaining a null at the secondary pick-off means, in which the ratio SF_{QUAD} over $SF_{IN-PHASE}$ is measured from the secondary 25 control loop to provide a direct measurement of $\text{Sin}(\phi_{SD} + \phi_{PPO})$, according to the relationship;

$$SF_{QUAD} = SF_{IN-PHASE} \times \text{Sin}(\phi_{SD} + \phi_{PPO})$$

where SF_{QUAD} is the quadrature scale factor, $SF_{IN-PHASE}$ is the in-phase scale factor, ϕ_{SD} is the phase error in the secondary drive means and ϕ_{PPO} is the 30 phase error in the primary pick-off means, the total phase error ϕ_E is obtained directly from the measured $\text{Sin}(\phi_{SD} + \phi_{PPO})$ according to the relationship;

$$\phi_E = \phi_{SD} + \phi_{PPO}$$

and phase corrections applied to the secondary drive means and/or primary pick-off means to reduce the phase error ϕ_E and hence the quadrature bias error to enhance the performance of the gyroscope.

5 In this way the phase response of the control electronics may be accurately adjusted precisely to null the breakthrough of the contaminating quadrature signal on to the in-phase rate sensing channel to provide significant performance enhancement.

10 The method may be used with a gyroscope having a silicon vibrating structure particularly one having a substantially planar, substantially ring-shaped vibrating structure.

15 Preferably, when the method is used with a gyroscope having analogue primary and secondary control loops with variable value capacitors, the phase corrections are applied by varying the values of the variable value capacitors in the secondary control loop relating to the secondary drive means and/or the values of the variable value capacitors in the primary control loop relating to the primary pick-off means to adjust ϕ_{SD} and/or ϕ_{PPO} such that ϕ_E is minimised in value, as near to zero as possible.

20 Conveniently when the method is used with a gyroscope having digital primary and secondary control loops, the phase corrections equal to ϕ_E are applied to the secondary drive means via the secondary control loop in a manner such as to cross-couple in-phase and quadrature drive channels by an amount equal and opposite to the combined effect of the phase errors in the vibrating structure control system.

25 Alternatively when the method is used with a gyroscope having digital primary and secondary control loops the phase corrections equal to ϕ_E are applied to the primary pick-off means via the primary control loop in a manner such as to cross-couple in-phase and quadrature drive channels by an amount equal and opposite to the combined effect of the phase errors in the vibrating structure control system.

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Conveniently in-phase and quadrature signal components are each multiplied by $\text{Sin } \phi_{\text{CORR}}$ and $\text{Cos} \phi_{\text{CORR}}$, where ϕ_{CORR} is the phase correction, and the effective phase of each in-phase and quadrature channel adjusted according to the summations

5 $\text{Quadrature}_{\text{CORR}} = \text{Quadrature} \times \text{Cos} \phi_{\text{CORR}} + \text{In-phase} \times \text{Sin} \phi_{\text{CORR}}$

and

$$\text{In-phase}_{\text{CORR}} = \text{In-phase} \times \text{Cos} \phi_{\text{CORR}} - \text{Quadrature} \times \text{Sin} \phi_{\text{CORR}}.$$

Advantageously ϕ_{CORR} is adjusted in accordance with operating temperature of the gyroscope to maintain ϕ_E at a minimised value.

10 For a better understanding of the present invention, and to show how the same may be carried into effect, reference will now be made, by way of example, to the accompanying drawings in which;

Figure 1a is a schematic representation of a $\text{Cos } 2\theta$ carrier vibration mode not according to the present invention,

15 Figure 1b is a schematic representation of a $\text{Sin } 2\theta$ response vibration mode not according to the present invention,

Figure 2 is a schematic block diagram of a conventional control system for a Coriolis Vibrating Structure Gyroscope not according to the present invention,

20 Figure 3 is a schematic block diagram of a digital control system for a Coriolis Vibrating Structure Gyroscope not according to the present invention,

Figure 4 is a schematic block diagram of a digital control system for a Coriolis Vibrating Structure Gyroscope incorporating the ability to adjust the effective secondary drive phase within the software, according to the present 25 invention,

Figure 5 is a schematic block diagram of a digital control system for a Coriolis Vibrating Structure Gyroscope incorporating the ability to adjust the effective primary pick-off phase within the software, according to the present invention,

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Figure 6 is a schematic block diagram illustrating the functionality of the phase correction block of Figures 4 and 5,

Figure 7 is a plot of the Vibrating Structure Gyroscope in-phase rate and quadrature outputs for a range of rotation rates applied about the sensitive axis 5 for a conventional Coriolis Vibrating Structure Gyroscope not according to the present invention,

Figure 8 is a plot of the variation in the quadrature scale factor for a range of phase errors ϕ_E for a conventional Coriolis Vibrating Structure Gyroscope not according to the present invention, and

10 Figure 9 is a graphical representation of variation of the measured phase error ϕ_E over a range of operating temperatures for a conventional Coriolis Vibrating Structure Gyroscope with a constant phase correction applied at room temperature according to the present invention.

15 The method of the present invention for reducing bias error in a Vibrating Structure Gyroscope will be described with reference to a Coriolis gyroscope design using a substantially planar substantially ring shaped vibrating structure operating in a closed loop configuration. It is to be understood that this method may be applied to any vibrating structure operated in such a closed loop configuration.

20 GB Patent 2322196 describes a Vibrating Structure Gyroscope which may be fabricated using micro-machining techniques and which is suitable for use in high reliability, high volume applications. The Vibrating Structure Gyroscope consists primarily of a crystalline silicon planar ring vibrating structure externally mounted on eight compliant support legs to an external 25 frame (not shown). This gyroscope is typically driven in $\cos 2\theta$ vibration modes as shown schematically in Figures 1a and 1b. One mode as shown in Figure 1a is excited as the carrier mode. When the gyroscope is rotated around the axis normal to the plane of the ring vibrating structure Coriolis forces F_C , are developed which couple energy into the response mode shown in Figure 1b.

30 The magnitude of the force is given by;

$$F_C = 2MV\Omega_{APP}$$

----- (1)

where M is the modal mass, v is the effective velocity and Ω_{app} is the applied rotation rate. The carrier mode vibration amplitude is typically maintained at a fixed level. This also maintains the velocity, v , at a fixed level and hence ensures that the developed Coriolis forces are directly proportional to the 5 rotation rate, Ω_{app} . The amplitude of the motion induced by these Coriolis forces may be enhanced by accurately matching the resonant frequencies of the carrier and response modes. The motion is then amplified by the Q of the response mode giving enhanced device sensitivity. When operating in an open 10 loop mode the sensitivity (scalefactor) of the gyroscope will be dependent on the Q of the secondary mode, which may vary significantly over the operating temperature range. This dependence may be eliminated by operating the device in closed loop (force feedback) mode. In this mode the induced response mode motion is actively nulled with the applied force required to achieve this now being directly proportional to the rotation rate.

15 Closed loop operation may typically be implemented using conventional prior art control loops as shown schematically in Figure 2. In Figure 2 the ring shaped vibrating structure 1 is excited into carrier mode resonant motion by a primary drive means 2 which motion is detected by primary pick-off means 3. The signal detected at 3 is demodulated at demodulators 4 prior to application 20 to the carrier mode control loops 5 and re-modulated at re-modulator 6 before application to the primary drive means 2. The carrier mode control loops 5 include a phase locked loop 7 which compares the relative phases of the primary pick-off and primary drive signals and adjusts the frequency of a voltage controlled oscillator 8 to maintain a 90° phase shift between the applied drive 25 and vibrating structure motion. This maintains the motion at the resonance maximum. The primary pick-off signal is also applied to an automatic gain control loop 9 which compares the primary pick-off signal level to a fixed reference level V_0 . The primary drive level is adjusted accordingly in order to maintain a fixed signal level and hence amplitude of motion of the vibrating 30 structure 1 at the primary pick-off means 3.

 The response mode motion of the vibrating structure 1 is detected at secondary pick-off means 10. The output signal from means 10 is demodulated

at demodulators 11 to separate the in-phase and quadrature components of this signal with the in-phase component being passed to an in-phase loop 12 and with the quadrature component of this signal being passed to a quadrature loop 13. The in-phase component is that which is at the same phase as the carrier mode motion. The Coriolis forces induced by applied rotation rates will generate motion with both in-phase and quadrature components. The quadrature component is an error term which arises due to the mode frequencies not being precisely matched. Loop filtering is applied to these demodulated base band DC signals by the loops 12 and 13 to achieve the required system performance such as bandwidth etc. The resultant signals are then remodulated at remodulators 14 and summed together by an adder 15 for application to secondary drive means 16 in order to maintain a null at the secondary pick-off means 10. The in-phase baseband signal, which is directionally proportional to the in-phase component of the response mode drive applied to the vibrating structure 1 via the secondary drive means 16 is scaled and filtered at filter 17 to produce a rate output signal 18.

For this mode of operation the scalefactor in response to an applied rotation rate, is given by:

$$SF_{RATE} = \frac{G_B V_O \omega}{k g_{ppo} g_{SD}} \quad \text{--- (2)}$$

where V_O is the primary mode amplitude set level, ω is the primary mode resonance frequency, k is a constant including the resonator dimensions, G_B is the Bryan factor (modal coupling coefficient), g_{ppo} is the primary pick-off gain and g_{SD} is the secondary drive gain.

The Vibrating Structure Gyroscope described in GB 2322196 may also be used in conjunction with a digital electronic control system such as described in GB 2329471. This conventional digital electronic control system is shown in Figure 3 of the accompanying drawings where like components previously described in respect of Figure 2 will be given like reference numerals and not further described in detail. For this implementation signals from the primary and secondary pick-off means 3 and 10 respectively, are digitised directly at

analogue to digital converters 19. The demodulation is then implemented in software 20 for both the in-phase and quadrature channels. The phase locked loop 7 and automatic gain control loop 9 functions are implemented as software functions. A digital control word is generated to drive the analogue voltage control oscillator 8 circuit at the carrier mode resonant frequency which controls the timing of the modulation and drive updates. The loop filters 12 and 13 respectively for the in-phase and quadrature channels of the secondary mode are also implemented in software 20. The drive levels to be applied to the primary and secondary drive means 2, 16 are calculated in the software algorithms and applied via digital to analogue converters 21. The secondary in-phase channel signal is filtered by the output filter 17 to give the appropriate characteristics for the rate output signal 18. In Figure 3 the automatic gain control set level input is shown at 22.

In an ideal case, that is with perfectly phased electronics and identical carrier and response mode frequencies for the vibrating structure 1, there will be no motion detected at the secondary pick-off means 10 when the gyroscope is not rotating. In reality, small geometric imperfections, arising during the gyroscope fabrication process, will give rise to a small splitting of the mode frequencies. This splitting will also tend to fix the angular position of the modes at an arbitrary angle, α , with respect to the primary drive means 2. When α is not equal to 0° the primary drive force will excite both modes to some extent. The phase locked loop 7 will adjust the drive frequency to achieve a 90° phase shift between the applied drive and the vibrating structure motion, as detected by the primary pick-off means 3. However significant motion will exist along the secondary axis which will be predominately in quadrature phase with respect to the primary motion. In a closed loop system this motion will be nulled by a quadrature force component applied by the secondary drive means 16.

The quadrature drive level required to null this signal is referred to as the quadrature bias and is defined as:

$$30 \quad \Omega_{QUAD} = K \times \Delta F \times \sin 4\alpha \quad \text{----- (3)}$$

where ΔF is the mode frequency split, α is the mode angle with respect to the primary drive axis and K is a constant including terms for the modal coupling coefficient and the secondary drive and primary pick-off gains.

Ω_{QUAD} can be large in comparison to the rate signals that the gyroscope 5 is required to measure. A typical rate measurement range for an automotive gyro of this type is $\pm 100^\circ/\text{sec}$. The quadrature bias may be large ($> \pm 100^\circ/\text{sec}$) in comparison to the rate signal and may vary significantly over the operating temperature range. Where a phase error, ϕ_E , exists a small proportion of this signal will appear on the rate channel. This will give rise to a rate bias error, 10 Ω_{Err} , which is given by:

$$\Omega_{Err} = K \times \Delta F \times \sin 4\alpha \times \sin \phi_E \quad \text{---- (4)}$$

Even relatively small phase errors can give rise to significant bias errors. A 0.5 degree phase error will result in a 0.87 deg/sec bias on the rate output for a $100^\circ/\text{sec}$ quadrature bias signal. Any temperature variation in the quadrature 15 signal or the phase error itself will cause this bias to vary which will severely limit the accuracy and stability of the gyro. In practical systems these phase errors can arise due to a number of factors including limitations of the accuracy of circuit component values (e.g. capacitors), rise times in drive amplifiers and variations in resonator operating frequency.

Achieving this level of accuracy and stability over temperature is quite 20 challenging in any practical electronic control system. It is also extremely difficult and time consuming to measure phase shifts to this level of accuracy using conventional techniques and equipment. It is therefore not possible to significantly reduce the rejection ratio of the quadrature bias in conventional 25 MEMS Coriolis gyroscope systems in a cost effective manner.

Accurate measurement of the magnitude of the phase error, ϕ_E , is 30 possible using information available on the secondary quadrature drive channel. This measurement is not typically recorded as a gyroscope output but can be observed relatively easily, particularly when using the digital control loops of GB 2322471. Any variation in this signal when the gyroscope is rotated is indicative of a phase error. The origin of this effect is described below.

The phase error, ϕ_E , is measured with respect to the primary resonance motion. The phase locked loop 7 locks on to the primary motion, as measured by the primary pick-off means 2 and provides a logic signal which acts as a reference to control the phasing/timing of the demodulation and re-modulation processes for both the in-phase and quadrature channels. When the gyroscope is rotated a Coriolis force is developed which is in-phase with the primary motion. In a perfect system this force is directly nulled by an in-phase force component applied via the secondary drive means 16. A phase error, ϕ_{SD} , in the secondary drive means 16 will therefore result in some of the signal required to generate the nulling force appearing in the quadrature channel. Similarly, a phase error in the primary pick-off means 3, ϕ_{PPO} , will give rise to an error in the timing of the reference logic signal in the electronics which will propagate into the secondary loops effectively cross-coupling the in-phase and quadrature channels. The secondary pick-off signal is maintained at a null by the force feedback and therefore the accuracy of this phase response is of less concern. A primary drive phase error will result in the primary oscillation frequency being slightly away from the resonance maximum. While this will introduce a small reduction in the drive gain this will not effect the bias as the phasing is referred back to the primary resonance motion. Phase errors in the secondary pick-off and primary drive will not give rise to bias errors and are therefore of less concern.

The rate dependence of the quadrature signal is given by:

$$SF_{QUAD} = SF_{IN-PHASE} \times \sin(\phi_{SD} + \phi_{PPO}) \quad \dots \quad (5)$$

Measurement of the ratio of the in-phase and quadrature scalefactors therefore gives a direct measurement of $\sin(\phi_{SD} + \phi_{PPO})$ from which the total phase error ($\phi_E = \phi_{SD} + \phi_{PPO}$), can be obtained directly. Measurement of the total phase error using this technique has the advantage that it can be performed on a completed gyroscope assembly without the requirement for any additional equipment or mechanical test procedures. The normal calibration procedure for any Coriolis gyroscope requires the assembly to be rotated at a range of known rotation rates on a rate table. This procedure provides a measurement of the

rate scalefactor, SF_{RATE} , and allows this parameter to be adjusted to a pre-set value using well known techniques. Simply recording the data available on the quadrature channel provides a measurement of SF_{QUAD} and hence ϕ_E .

Thus the method of the present invention for reducing bias error in a
5 Vibrating Structure Gyroscope having a vibrating structure 1, primary drive
means 2 for putting the vibrating structure 1 into carrier mode resonance,
primary pick-off means 3 for sensing carrier mode motion, secondary pick-off
means 10 for sensing response mode vibration of the vibrating structure 1 in
response to applied rotation rate, closed loop primary control loops for
10 maintaining a fixed amplitude of motion at the primary pick-off means 3 and for
maintaining the drive frequency at the resonance maximum, and secondary
control loops for maintaining a null at the secondary pick-off means 10, includes
the steps of measuring the ratio SF_{QUAD} over $SF_{IN-PHASE}$ from the secondary
15 control loop to provide a direct measurement of $\text{Sin}(\phi_{SD} + \phi_{PPO})$ according to
the relationship (5) given above where SF_{QUAD} is the quadrature scale factor,
 $SF_{IN-PHASE}$ is the in-phase scale factor, ϕ_{SD} is the phase error in the secondary
drive means 16 and ϕ_{PPO} is the phase error in the primary pick-off means 3.
The total phase error ϕ_E is obtained directly from the measured $\text{Sin}(\phi_{SD} + \phi_{PPO})$
according to the relationship;

20
$$\phi_E = \phi_{SD} + \phi_{PPO} \text{ as given above}$$

and phase corrections are applied to the secondary drive means 16 and/or
primary pick-off means 3 to reduce the phase error ϕ_E and hence the quadrature
bias error to enhance the performance of the gyroscope.

When the method of the present invention is used for the gyroscope
25 having analogue primary and secondary control loops with variable value
capacitors (not shown) the phase corrections are applied by varying the values
of the variable value capacitors in the secondary control loop relating to the
secondary drive means 16 and/or the values of the variable value capacitors in
the primary control loop relating to the primary pick-off means 3 to adjust ϕ_{SD}
30 and/or ϕ_{PPO} such that ϕ_E is minimised in value. Thus as the requirement is for ϕ_E

= 0 this can be conveniently achieved by adjusting either ϕ_{SD} or ϕ_{PPO} provided
 $\phi_{SD} + \phi_{PPO} = 0$.

Adjustment of ϕ_E is more easily accomplished using the digital electronic control system of GB 2322196. A phase correction can be introduced within the 5 software of the control loop algorithms as shown schematically in Figure 4 where the correction is applied to the secondary drive means 16. Again in Figure 4 parts previously shown in Figures 2 and 3 and previously discussed will be given like reference numerals and not specifically described in further detail. Thus in this context in the method of the present invention when used 10 with a gyroscope having digital primary and secondary control loops the phase corrections equal to ϕ_E are applied to the secondary drive means 16 via the secondary control loop in a manner such as to cross-couple in-phase and quadrature drive channels by an amount equal and opposite to the combined effect of the phase errors in the vibrating structure 1. In the Figure 4 15 arrangement ϕ_{CORR} is applied to a phase correction unit 24 connected between the remodulators 14 and the adder 15. A further remodulator 23 is located between the voltage controlled oscillator 8 and the automatic gain control filter 9.

This correction can alternatively be applied to the primary pick-off 20 means 3 as shown in Figure 5 in which like components previously described and referenced will be given like reference numerals and not described further in detail. In the Figure 5 arrangement the phase correction unit 24 is located in the primary control loop for application to the primary pick-off means 3 so as to cross-couple in-phase and quadrature drive channels by an amount equal and 25 opposite to the combined effect of the phase errors in the vibrating structure 1. To this end the phase correction unit 24 is located between the quadrature and in-phase demodulators 4 and the phase locked loop filter 7 and automatic gain control loop filter 9 as shown in Figure 5.

The functionality of the phase correction is shown in Figure 6 in which 30 again like features previously described have been given like reference

numerals and will not be further described in detail. An adder 25 and a differencer 26 are included.

When applied on the secondary drive, the in-phase and quadrature components are each multiplied by $\sin\phi_{CORR}$ and $\cos\phi_{CORR}$ and the effective 5 phase of each channel adjusted by applying the following summations:

$$\text{Quadrature}_{CORR} = \text{Quadrature} \times \cos\phi_{CORR} + \text{In-Phase} \times \sin\phi_{CORR} \quad \dots \quad (6)$$

$$\text{In-Phase}_{CORR} = \text{In-Phase} \times \cos\phi_{CORR} - \text{Quadrature} \times \sin\phi_{CORR} \quad \dots \quad (7)$$

The gyroscope scalefactor information is conventionally obtained by measuring the uncalibrated gyroscope output over a range of applied rotation 10 rates. A typical data set obtained for the in-phase rate channel is shown in Figure 7. The scalefactor for in-phase is obtained from the slope of the line 27. The equivalent line 28 for the quadrature channel is also shown in Figure 7. The finite slope of line 28 is indicative of a phase error.

The correlation of SF_{QUAD} with ϕ_E is shown in Figure 8. This data was 15 obtained from SF_{QUAD} measurements over a range of values of ϕ_{CORR} . The offset is attributable to a known hardware phase error. The resolution achievable is clearly visible from this graph and indicates that it is possible to set the phase to an accuracy of $<0.05^\circ$. This represents over an order of magnitude improvement in the calibration accuracy of this parameter and is 20 equivalent to a reduction in the contribution of the quadrature bias error, Ω_{ERR} , from $0.87^\circ/\text{s}$ to $<0.087^\circ/\text{s}$.

An additional advantage when applying the method of the invention in conjunction with digital control electronics is that it is possible to adjust the phase compensation dependent upon the ambient temperature of the gyro. 25 Coriolis gyroscopes are required to operate over a temperature range of -40°C to $+85^\circ\text{C}$ in typical applications. The phase errors within the hardware are known to vary, in a systematic manner, over this range. The measured variation for a typical automotive sensor is shown in Figure 9. The phase error for this sensor has been corrected, using the method of the present invention, to 30 be approximately zero at room temperature. In any application requiring high

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performance it is usual to provide a direct measurement of the sensor ambient temperature. This is typically achieved by incorporating a temperature sensor within, or in close proximity to, the gyroscope. If the temperature variation of the phase error is known then ϕ_{CORR} can be adjusted in accordance with the measured temperature using a simple algorithm function in order to maintain $\phi_E \sim 0^\circ$. For high performance applications it is necessary to characterise the sensor performance over the full operating temperature range. The test procedure involves measurement of the bias and scalefactor at a range of temperatures. The quadrature scalefactor, SFQUAD, may also be readily recorded as part of this procedure to provide the necessary data on the temperature variation of ϕ_E .